

RESEARCH AT THE INSTITUTE OF ELECTROTECHNOLOGY IN THE FIELD OF INDUCTION HEATING

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Annotation — The paper informs generally about the activities at the Institute of Electrotechnology in Hannover, Germany in the fields of education and research in Electrotechnology. Several actual research projects are described in detail in the field of induction heating. A second paper written by Baake and Spitans gives an overview about the activities at the institute in induction melting.

Keywords: *Electrotechnology, induction heating.*

INTRODUCTION

At the Institute of Electrotechnology (ETP), belonging to the Department of Electrical Engineering and Computer Science at the Leibniz University Hannover, are carried out research and development projects for industrial applications of Electrotechnologies [1]. The research and development priorities of the Institute are in the field of induction heating for melting and heating, in the field of magneto-hydrodynamics and the electromagnetic processing of materials.

The research activities of the institute (Pic. 1) are handled in two divisions:

- the division „**Thermal processes and electromagnetic processing of materials**“, managed by Prof. Nacke and
- the division „**Magnetofluidynamic processes and sustainable use of resources**“, managed by Prof. Baake.

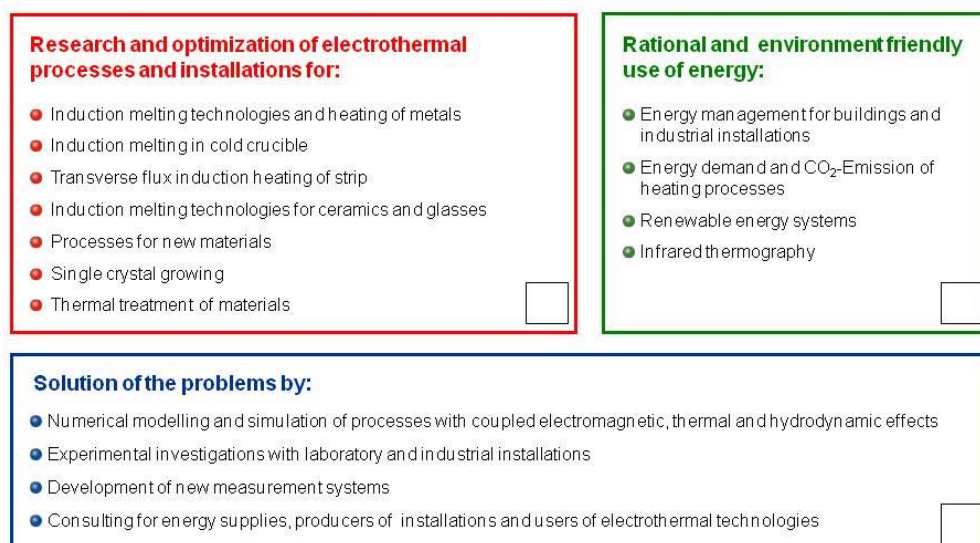
The magneto-hydrodynamics research field is covering projects for the analysis and the optimization of magnetofluidynamic processes and installations.

An important area is the electromagnetic processing of materials including the processing of non-linear electrothermal and magnetofluidynamic systems. Most of the current research and development projects in the field of electrothermal process technology are focused on induction heating and melting.

Activities in the field of efficient and environment-friendly use of energy include examinations of the impact of various energy sources on primary energy demand and CO₂-emissions of industrial process heat applications. Analysis and shielding of electromagnetic stray-fields in the vicinity of induction heating installations are also a part of this working field. A third task is thermal analysis and energy demand management of buildings and industrial plants.

Most of the projects are performed in close cooperation with partners from industry and other research institutions. The activities reach from application oriented pure research to industrial development projects, including examinations in the field of efficient, environment-friendly use of energy within the industry.

Research, Development, Consulting and Service



Pic. 1. Main research areas at the Institute of Electrotechnology of Leibniz University Hannover

At ETP actually 14 scientific staff members beside the director and the academic director are employed. 40 % of the staff costs are paid by the Federal State Lower Saxony, 60 % of the staff costs are paid by research projects. The financial means are coming from German foundations like DFG, AiF, BMBF, BMWi, from the European Commission or directly from industry.

STUDY COURSES

The courses offered by ETP include lectures and exercises in the amount of 25 hours per week for students of electrical engineering and mechatronics in undergraduate and graduate courses.

In the basic studies, the courses "Technical Heat Transfer" for electrical and mechatronic engineers are offered.

In the specific studies the courses "Electrothermal Processes", "Industrial Electroheat", "Modelling of Electrothermal Processes" and "Heating and Cooling in Electrical Engineering" are offered by Prof. Nacke and the course "Magnetofluidynamic" is offered by Prof. Baake. Additional courses are given by external lecturers.

The further study courses consist of advanced level laboratories for temperature measurement and electroheat processes, a project work entitled "Modelling in Energy Technology" as well as the supervision of bachelor and master theses.

RESEARCH AREAS

Most of the current research and development projects in the field of Electrotechnology are focused on induction through heating, induction surface hardening, hybrid processes with combination of induction heating and laser welding, induction melting of metals, oxides and glasses as well as electromagnetically supported crystal growth. Along with many new developments in the area of common ferrous and non-ferrous metals, there has been an increase in projects concerning innovative materials for high technology applications, such as semiconductor silicon, titanium or titanium-aluminium alloys and oxides with high melting points.

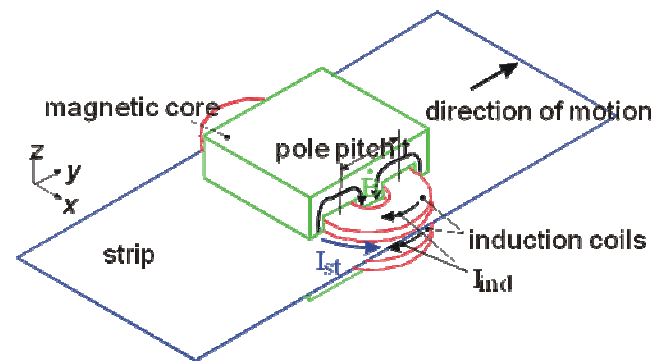
In the following some selected working areas in Induction Heating are described.

Development and investigation of flexible transverse flux strip heaters

Many production lines in the semis industry include the heating of thin metal strips in continuous operation as an important process step. For heating there is a wide variety of applications ranging from drying tasks after coating and painting, galvanizing, the heat treatment (e.g. annealing) to the heating for hot forming. Nowadays mainly gas or electrically resistance heated furnaces are used for these tasks. They work on the principle of indirect heat transfer. The energy is supplied to the material to be heated by convection and heat radiation to the surface thereof. In this way, there are limitations and disadvantages, such as the limited achievable power density, increased scale attack and

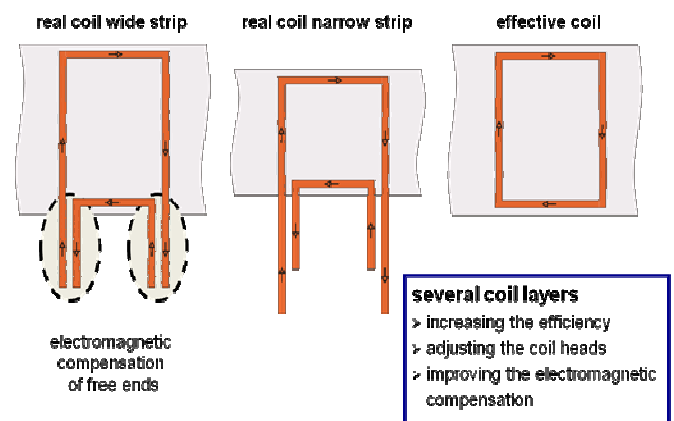
grain growth due to the long residence time in the furnace. At the same time, the operational characteristics such as large floor space required, high heat losses and extended up and cool-down by the large volume furnace rooms and the limited flexibility of these systems are very disadvantageous for modern production processes.

An innovative solution to the problems described above can be achieved by the use of the transverse flux induction heating concept [2, 3]. This technology offers numerous advantages such as high power density, high efficiency, high automation and flexibility. The schematic structure of a transverse flux induction heater is shown in Pic. 2.



Pic. 2. Schematic structure of a transverse flux induction heater

In recent years, extensive work in the field of transverse flux heating has been carried out at ETP. The achieved good results are mainly based on two facts. This is both a design concept developed at the institute and the other using a combination of numerical simulation and mathematical optimization algorithms [4]. In the mathematical optimization search the algorithms look for any special parameter set to get the optimal design of the inductors. The focus of developments in recent years in the field of transverse flux technology aimed at the use of heaters for strips of variable width. Pic. 3 shows the newly developed and patented ETP concept for heating the metal strips of variable width (VABID). It is ideal for many applications, extremely robust and has now been proven successful in industrial use.



Pic. 3. Transverse flux heating concept VABID for strips of variable width

Induction surface hardening

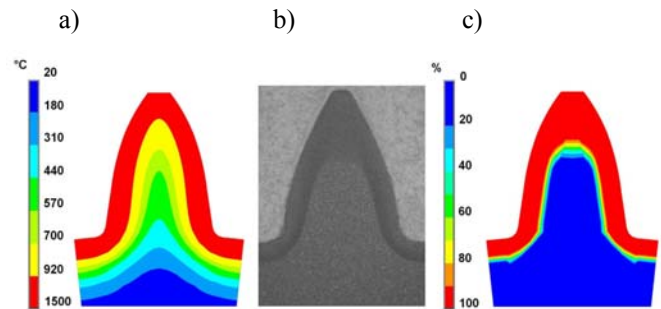
Another focal point of research at ETP is inductive surface hardening. This innovative electro thermal technology is used for improving the quality of mechanical components in terms of abrasion resistance while preserving the core ductility. To receive these properties, a thin layer of material underneath the work piece's surface is heated up by induction and quenched afterwards. The main advantages of this technology are a very short process time, high power densities, low distortion and low space requirements. Therefore subsequent machining can often be eliminated and an integration of the process into production lines can be achieved easily.

The design of induction hardening devices, especially the inductor geometry and the choice of the hardening parameters like inductor current and power, are actually carried out by experience and experimentation. However, there are limits to this approach if complex work piece geometries have to be handled or if the hardening parameters become more complex, for example when two simultaneous frequencies are used. Also, a design based on experimentation often means a big financial effort and is time consuming.

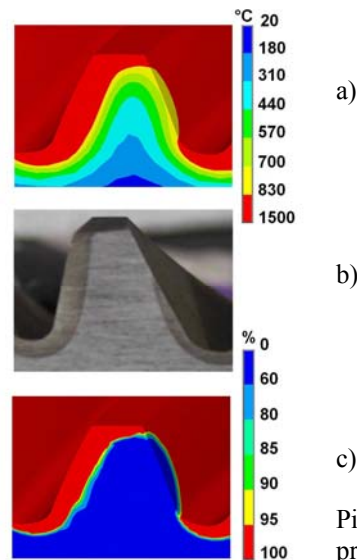
The numerical simulation of induction heating processes offers new opportunities for the design of induction hardening devices with complex geometries and time regimes. At ETP, a model was developed which can successfully simulate the full in-stationary heating process [5, 6]. The model allows the solution of the coupled non-linear electromagnetic and thermal fields taking into account all relevant temperature and field dependencies of the material properties, which change significantly during heating. A method to simulate the heating process with several simultaneous frequencies was implemented as well. Relative motion of work piece and inductor, for instance rotation of a work piece, can also be simulated. Subsequent to heating, the quenching process and phase transformations within the material are calculated based on the time-temperature profile. All process parameters can be changed easily. Therefore, the simulation tool is able to investigate the influence of different hardening parameters on the hardening profile and to optimize the process.

The simulation tool was used to design and optimize a broad range of processes over the last years. For example, work pieces like worm, spiral and straight cut gears as well as crankshafts were investigated. Experiments were used to validate and improve the simulation tool constantly. In principal, any 3D geometry can be investigated with the ETP model. The complexity is only limited by calculation time.

Pic. 4 shows three cross sections of a hardened straight cut gear. Pic. 5 shows the edge of a tooth of a hardened helical gear. The calculated temperature profile after heating, a microsection and the calculated martensite content are displayed. In both cases, the same process parameters were used in the simulation and in the experiment. The computed results and the microsections show good agreement.



Pic. 4. (a) Temperature profile, (b) microsection and (c) martensite profile of a straight cut gear



Pic. 5. (a) Temperature profile, (b) microsection and (c) martensite profile of a helical gear

Induction assisted welding processes

Nowadays laser applications are used for many different welding processes in the steel industry. This method offers advantages like high focused energy input that leads to a selective heat generation in the welded joint without involving surrounded areas. This energy respective advantage results on the other hand in unfavorable high temperature gradients. Especially at high carbon steels these temperature gradients and the following high cooling rates are effecting a significant enhancement of the hardness and the brittleness as well. An induction post-heating process (Pic. 6a) allows a concentrated heat generation in the workpiece and the welded joint to decrease the temperature gradients, the cooling rates and so the hardness and brittleness. The induction annealing process enables an effective possibility to improve the material's microstructure.

Also an induction preheating process (Pic. 6b) offers advantages like the reduction of the necessary welding power or the increasing of the speed of motion due to the increased temperature in the material. Furthermore it leads to high

implemented thermal energy around the welded joint that decreases the cooling rates and better the microstructure.

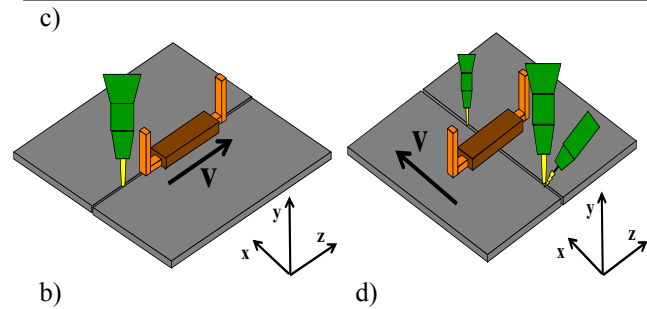
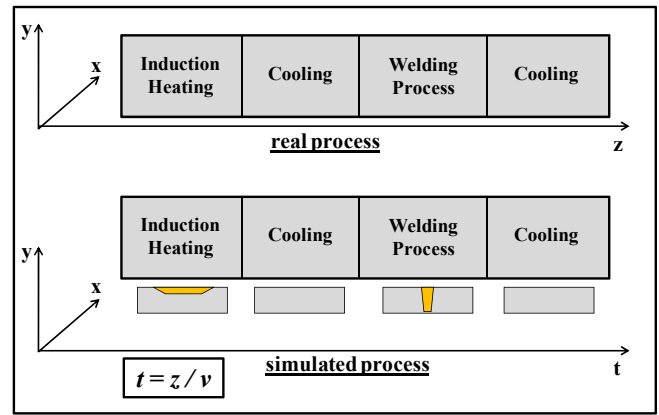
During different projects that had been accomplished in collaboration with the Lasercenter Hannover (LZH) the combined implementation of induction heating and laser welding were investigated and promising solutions were estimated [7, 8, 9]. One of the first applications was used for the laser welding process of galvanized high strength steels with an induction post-heating support. The corresponding induction process was designed and optimized at ETP by use of numerical simulation (Pic. 6c).

Many projects were executed with LZH so far. The aim of an already finished EU-project that was carried out with ten project partners was the improvement of welding methods of high strength steels to achieve a propagated usage of these materials in different industrial applications. In the framework of these investigations also welding processes in combination with induction heating of materials with thicknesses up to 40 mm were analyzed.

Therefore also welding methods with plasma arc and metal gas arc were taken into account. In this case the influence of both the induction preheating and the induction post-heating were investigated at ETP. A current project that is also conducted in cooperation with LZH contains a preparatory low power laser welding process to contact two steel sheets of high thickness that have to be welded. A following and perpendicularly directed inductor is implemented to assist the final laser and metal gas arc welding process (Pic. 6d).

Within a further project that was accomplished in collaboration with LZH a new procedure was developed that contains an induction preheating, a laser welding process and a following inductive hardening process by use of the same inductor that was already established for the preheating procedure. For this reason the thermal energy of the preheating process is used to assist the welding process.

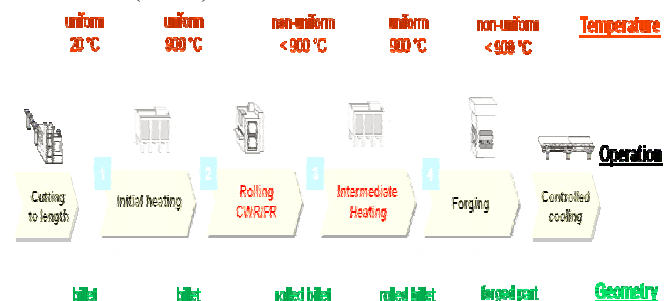
Both the preheating energy and the welding energy support the finishing hardening process to achieve a very energy effective process. This combined process enables the transformation of the welded areas to hardened functional areas.



Pic. 6. Inductive assisted welding processes

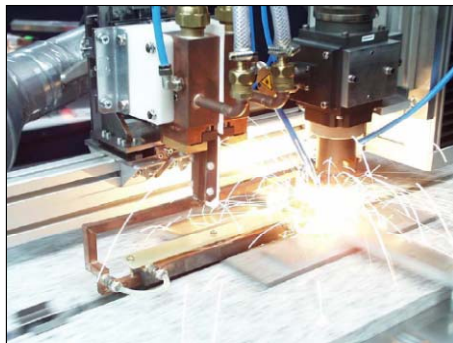
Induction reheating operation within a warm forming process chain

Warm forging at temperatures between 600°C and 900°C is an economical alternative to conventional hot forging technology (usually at 1250°C) providing reduced energy input, minimal scale, reduced decarburization and surface roughness and closer tolerances. On the other hand, more forging operations are necessary as the tool material can only withstand limited loads. For this reason, pre-forming by additional rolling operation is a suitable way for obtaining the required mass distribution. Nevertheless, every pre-forming operation causes additional reduction of the work piece temperature that directly affects the following forging sequence. That is why an intermediate heating able to compensate temperature losses due to warm rolling within a short cycle time is needed for optimal warm forging conditions (Pic. 7).



Pic. 7. Warm forging process chain with induction reheating operation

In frame of the European research project DeVapro - "Development of a Variable Warm Forging Process" both warm rolling and induction reheating are developed, with the aim to broaden the spectrum of producible geometries, increase the production output, and improve the final work



a)

piece properties making the warm forging technology more variable [10, 11].

An intermediate induction heating has been developed and integrated into a warm forging line to compensate the thermal losses occurring during the pre-forming operation by means of cross wedge rolling. The experimental verification by means of heating tests has confirmed the system performance to reheat the rolled billets within the required time and temperature tolerance. In this way, optimal forging conditions can be achieved within the current cycle time.

The energy consumption of the warm forging method is 23 % lower than hot forging method providing (beside the forging related improvements) significant reduction of the heating costs.

The developed method can be also beneficial in other forging processes requiring reheating of partially completed forgings. The main advantage of this approach is the possibility of a very fast and selective heating providing homogeneously heated parts for further forging operations. Additionally, this approach offers a new freedom in design of new forming sequences which consider temperature sensitive materials (Titan alloys) or complicated geometrical shapes (crankshafts).

Optimization of crystal growth processes by the use of electromagnetic fields

The growth of single silicon crystals with large diameters is one of the key enabling technologies for the further successful development of micro and power electronics. In cooperation with an industry partner ETP has developed new processes for the growth of single crystals up to 300 mm diameter. The silicon single crystals must meet the highest demands on the purity of the material and the uniformity of the crystal structure. The magnification of the crystal diameter is essential in order to ensure the necessary productivity gains in future chip generations and components.

Silicon single crystals are produced with two different crystal growth processes. The floating zone (FZ) process (Pic. 8a) is used for the production of single crystals for the power electronics. In this case a feed polycrystalline silicon rod is melted from top by induction. The single crystal is growing below the melting zone located between the polycrystalline rod and the single crystal. It is slowly pulled down until the feed rod is depleted. At the Czochralski (CZ) method (Pic. 8b), which is used for production of single crystals for microelectronics, silicon is melted in a quartz crucible heated by resistance heaters. The resulting single crystal is pulled upward from the silicon melt.

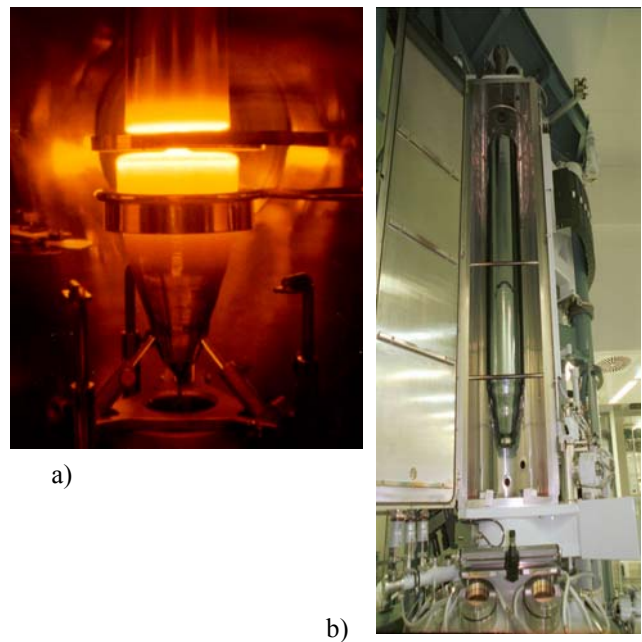
At ETP in particular the melt flow and the associated heat and mass transfer in industrial growth processes are numerically simulated and analyzed in parametric studies in cooperation with the University of Latvia [12, 13]. For these investigations mathematical models are developed and implemented in own software codes or in extensions to commercial software packages.

In the simulation of the FZ process, the model chain consists of the calculation of the electromagnetic field, the temperature field, the melt flow, the solid/liquid interface and the transport of the dopant as well as the calculation of the macroscopic and microscopic resistivity distribution in

the final wafer. In the simulation of the CZ method the turbulent melt flow and the coupled temperature field are calculated.

One aim of the simulations is the investigation and analysis of the highly complex effects inside the silicon melt where measurements are very difficult. The results are applied in order to improve the crystal properties and the growth process, such as the dopant and oxygen distribution and especially the crystal structure. Additional electromagnetic fields are a flexible measure in order to influence the melt flow. With the help of software tools corresponding inductors were designed and optimized. In addition, the simulations can compensate the extremely high cost of experiments and thus keep the development costs in an economically acceptable level.

The numerical simulations and the application of the numerical models for induction heating or for electromagnetic processing of materials have increasingly found applications in recent years also for other semiconductor materials such as GaAs, InP, and Ge, as well as for the growth of solar silicon. At ETP several projects were carried out in recent years in order to optimize the growth process, to improve the productivity or the quality of solar crystals using different methods like the Edge-defined film-fed growth process (EFG), the String Ribbon process or the direct casting of silicon crystals.



Pic. 8. Floating zone process (a) and large single silicon crystal grown by Czochralski process (b)

Induction skull melting of oxides and glass

The production of high-technology products such as optical glasses, synthetic gemstones, superconductors and laser crystals needs very high quality standards. The powdery raw materials such as ceramics, glass and oxides are melted at temperatures of up to over 3000°C and in most cases lead to chemically aggressive melts. Conventional melting processes cannot be used for such extreme conditions. The induction skull melting technique (ISMT) is

very suitable for induction high-temperature melting of low electrically conductive materials like oxides and glass.

Against this background, ETP operates one in design and size unique experimental installation for melting oxides and glasses by the skull melting method (Pic. 9).

The melting process can take place either in air, in vacuum or in inert gas atmosphere. The material can be melted either in a water-cooled slitted metal crucible (cold crucible) which is surrounded by an inductor or in an inductor crucible which is the crucible and the inductor by itself. A lowering device allows the directional solidification of the melt which is necessary for the growth of large oxide crystals. The power supply consists of a high-frequency transistor converter with an output power of 320 kW and an output voltage of maximum 900 V in the frequency range from 80 to 350 kHz.

With the high temperature melting installation different oxide materials, such as ZrSiO_4 , ZrO_2 , Al_2O_3 , superconductor materials and various glasses are melted [14, 15]. In some cases crystals were grown from oxides. Besides the interest in melting of oxides and glass materials the so-called 'Miscibility gap' phenomenon of mixed oxides has been investigated. This is a phenomenon in which the fully mixed oxide separates in the molten state at a certain temperature. This condition is similar to the two-phase system, for example, water and oil. The use of this phenomenon can, similar to the hardening of steel, lead to new and improved properties of mixed oxides, eg. of the ZrO_2 - Al_2O_3 2-phase-system.



Pic. 9. Skull-Melting-Installation at ETP

OUTLOOK

The Institute of Electrotechnology in Hannover will concentrate its teaching and research activities also in the future on the development of electrothermal and electromagnetic processes as well as the investigation of the efficient and environmental friendly use of energy in industry. In particular the manufacturing of new materials and new products offers future potentials for innovative solutions applying electrothermal and electromagnetic processes. The multifarious contacts to equipment manufacturer, to the equipment users and to energy suppliers ensure the praxis relevance of the work of the ETP. Due to

the close contact to the industrial praxis also the teaching activities will be oriented on the status quo of science and technology. In particular the integration of the students and scientific collaborators into the industrial oriented research activities guarantees the important relationship between teaching and praxis.

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